Low-mass dileptons and dropping rho meson mass

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Abstract

Using the transport model, we have studied dilepton production from heavy-ion collisions at Bevalac energies. It is found that the enhanced production of low-mass dileptons observed in the experiment by the DLS collaboration cannot be explained by the dropping of hadron masses, in particular the ρ-meson mass, in dense matter.

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One of the most exciting physics one expects to learn from relativistic heavy-ion collisions is the possibility to create nuclear matter at densities larger than that in the center of normal nuclei and possibly comparable to that in the interior of neutron stars [1–3]. This thus offers the opportunity to study if the nuclear equation of state becomes softened at high densities as required from studies of supernova explosions. The high density nuclear matter created in these collisions also makes it possible to study how spontaneously broken chiral symmetry, which is characterized by a large value of the quark condensate in the vacuum, is partially restored when the temperature and density of matter becomes high, as predicted by theoretical studies [4]. Unfortunately, a direct relation of the quark condensate to physical observables has not been rigorously established [5]. One conjecture has been suggested by Brown and Rho [6] that masses of non-strange hadrons such as nucleon, ρ, and ω, are reduced in the nuclear medium and are proportional to the in-medium quark condensate. Dropping hadron in-medium masses have also been found in some theoretical models, such as the QCD sum rules [7], the quark-meson coupling model [8], and the hadronic model including vacuum polarization effects [9]. Such scaled in-medium hadron masses have been shown to lead to significantly improved understanding of many nuclear phenomena, such as the enhanced axial charge transitions seen in heavy nuclei [10] and the quenching in the longitudinal response function of nuclei [11].

A more direct evidence for a dropping ρ-meson mass seems to be provided by the enhanced production of dileptons with invariant mass around 400-500 MeV above known sources of dileptons in the CERES experiment of heavy-ion collisions at CERN SPS [12]. In theoretical studies [13–17] based on various models ranging from a simple thermal model to sophisticated transport models, dilepton production has been investigated by including contributions not only from the Dalitz decay of mesons and direct dilepton decay of vector mesons but also from pion-pion annihilation. The latter is practically absent in proton-nucleus collisions and is found to account for only about half of the observed enhancement

in heavy-ion collisions. Including contributions from other processes such as the a_1 decay [18] and pion-rho scattering [19] does not help much. On the other hand, allowing for the reduction of the ρ meson in-medium mass in the relativistic transport model [13,14,17], it has been shown that it can indeed lead to a further enhancement of low-mass dileptons as observed in the experimental data. On the other hand, it has also been claimed [20] that if the ρ meson – which in free space has a broad decay width to two pions – melts in the medium due to additional decay channels such as the resonance-hole states [21–23], would also significantly increase the yield of low-mass dileptons. However, in the dynamical studies of Ref. [24] the ρ spectral function, which consists of effects due to both medium modifications of pions and the baryon-resonance-nucleon-hole excitations, is introduced through pion-pion annihilation to dileptons via the vector meson dominance. Because of the large pion to nucleon ratio (about 5) in heavy-ion collisions at SPS energies, the effect of resonance-hole contributions to dilepton production is thus overestimated in these studies.

Dileptons have also been measured in heavy-ion collisions at the Bevalac by the DLS collaboration [25,26] at incident energies that are two orders-of-magnitude lower than that at SPS. Although the first published data [25] based on a limited data set are consistent with the results from transport model calculations [27,28] that include pn bremsstrahlung, π^0, η and Δ Dalitz decay and pion-pion annihilation, a recent analysis [26], including the full data set, shows a considerable increase in the cross section, which is now more than a factor of five above these theoretical predictions even after including also contributions from the decay of ρ and ω that are produced directly from nucleon-nucleon and pion-nucleon scattering in the early reaction phase [29,30]. With an in-medium rho spectral function as that used in Ref. [24] for dilepton production from heavy-ion collisions at SPS energies, dileptons from the decay of both directly produced ρ's and pion-pion annihilation have been considered, and a factor of two enhancement has been obtained compared to the case of using a free ρ-spectral function. Since the pion to nucleon ratio in heavy-ion collisions at Bevalac energies is much smaller than one (about 0.2), contrary to that in heavy-ion collisions at SPS energies, the contribution of pion-pion annihilation instead of baryon resonance Dalitz decay is overestimated in the spectral function analysis in Ref. [29]. As dropping hadron masses in dense matter have been seen to account for the observed enhancement of low-mass dileptons in heavy-ion collisions at SPS energies, it is of interest to see if this can also explain the enhanced production of dileptons at Bevalac energies.

We shall base our study on the Hadron String Dynamics (HSD) model [31], which describes the collision dynamics by propagating nucleons in a mean-field potential given by the attractive scalar and repulsive vector potentials. Free nucleon-nucleon cross sections are used in treating their collisions, which include both elastic and inelastic ones. The latter leads to the production of both meson resonances such as ρ and ω and baryon resonances such as $\Delta(1232)$, $N^*(1440)$, and $N^*(1535)$. The decay of baryon resonances then leads to the production of pions and η's. Scattering of pions with nucleons is also included, leading to the production of meson and baryon resonances as well. This model has been shown to give very good descriptions of the measured yield of pions and η's as well as the rapidity and transverse momentum distributions of hadrons [32].

To study dilepton production, we include contributions from pn and πN bremsstrahlung; Dalitz decay of π^0, η, ω, Δ, and $N^*(1440)$; and direct decays of ρ and ω. All contributions will be treated in the standard way as in Refs. [27–29,33]. However, since vector meson

production in nucleus-nucleus collisions at Bevalac energies, which are below the production subthreshold in nucleon-nucleon collisions, is dominated by the πN channels [34], we shall pay a special attention to this contribution. In particular, it has been recently shown that the rho meson couples strongly to $N^*(1520)$ [23,35], we shall thus include additionally this effect in rho meson production from πN scattering, as it has been overlooked in previous work.

Specifically, the isospin-averaged production cross section of a neutral ρ meson from πN scattering through $N^*(1520)$ at a center-of-mass energy $\sqrt{s}$ is

$$\frac{d\sigma_{\pi N \to \rho N}(s, M)}{dM} = S_{\pi N} \frac{4\pi}{k_\pi^2} \frac{s \Gamma_{N^* \to \pi N}(\sqrt{s})}{(s - m_{N^*}^2)^2 + s \Gamma_{tot}^{N^*2}(\sqrt{s})} \frac{d\Gamma_{N^* \to \rho N}(\sqrt{s}, M)}{dM}, \tag{1}$$

with

$$S_{\pi N} = \frac{1}{3} \frac{(2J_{N^*} + 1)}{(2J_\pi + 1)(2J_N + 1)} \frac{(2I_{N^*} + 1)}{(2I_\pi + 1)(2I_N + 1)},$$

where $J_{N^*} = 3/2, J_\pi = 0, J_N = 1/2, I_{N^*} = 1/2, I_\pi = 1$, and $I_N = 1/2$. In Eq. (1), k_π is the pion three-momentum in the center of mass of pion and nucleon.

The partial decay width of a $N^*(1520)$ of mass $\sqrt{s}$ to a nucleon and a ρ meson of mass M is given in Ref. [23], i.e.,

$$\frac{d\Gamma_{N^* \to \rho N}(\sqrt{s}, M)}{dM} = \left(\frac{f_{N^* N \rho}}{m_\rho}\right)^2 \frac{1}{\pi} M \frac{m_N}{\sqrt{s}} k_\rho (2\omega_\rho^2 + M^2) A(M) F(k_\rho^2), \tag{2}$$

where $f_{N^* N \rho} \sim 7$ is the coupling constant, k_ρ denotes the three-momentum of the ρ meson in the rest frame of $N^*(1520)$, and $\omega_\rho^2 = M^2 + k_\rho^2$ is its energy. The ρ spectral function is denoted by $A(M)$ and has a Breit-Wigner form,

$$A(M) = \frac{1}{\pi} \frac{m_\rho \Gamma_{tot}^\rho(M)}{(M^2 - m_\rho^2)^2 + (m_\rho \Gamma_{tot}^\rho(M))^2}. \tag{3}$$

The form factor $F(k_\rho^2)$ is taken to have a monopole form

$$F(k_\rho^2) = \frac{\Lambda^2}{\Lambda^2 + k_\rho^2}, \tag{4}$$

with $\Lambda = 1.5$ GeV.

The ρ meson total width $\Gamma_{tot}^\rho(M)$ is given by the sum of the width due to decay to two pions and that due to absorption by nucleons and elastic scattering, i.e.,

$$\Gamma_{tot}^\rho(M) = \Gamma_{\rho \to \pi\pi}(m_\rho) \left(\frac{m_\rho}{M}\right) \left(\frac{k_\pi(M)}{k_\pi(m_\rho)}\right)^3 \tag{5}$$
$$+ \sigma_{\rho N}(s, M) v \gamma \rho_N,$$

where $\Gamma_{\rho \to \pi\pi}(m_\rho) \sim 0.15$ GeV and k_π is the pion momentum in the rest frame of the ρ meson. The second term corresponds to the collisional broadening width and is given by the product of ρ-nucleon total cross section $\sigma_{\rho N}(s, M)$, the ρ meson velocity v in the rest frame

3

of the nucleon current, the associated Lorentz factor γ, and the nucleon density ρ_N. Based on the resonance model, the ρ-nucleon total cross section has been determined in Ref. [36], and the result can be parameterized as

$$\sigma_{\rho N}(s, M) = 26 + 15k_\rho^{-1.2} \text{ [mb]}, \tag{6}$$

with k_ρ [GeV/c] the rho meson three-momentum in the rest frame of the nucleon current. At normal nuclear matter density, this gives an average rho meson collisional width of about 75 MeV whereas in central ^{40}Ca+^{40}Ca reactions at 1 A·GeV the average collisional width amounts to $\simeq 140$ MeV.

The partial decay width of a $N^*(1520)$ to πN is [23]

$$\Gamma_{N^* \to \pi N}(\sqrt{s}) = \Gamma_0 \left(\frac{k_\pi(\sqrt{s})}{k_\pi(m_{N^*})} \right)^{2l+1}, \tag{7}$$

with $k_\pi(m)$ the pion three-momentum in the rest frame of $N^*(1520)$, $l = 2$, and $\Gamma_0 = 0.095$ GeV.

The total decay width of the $N^*(1520)$ is given by the sum of the partial decay widths to pion and ρ, i.e., $\Gamma_{\text{tot}}^{N^*} = \Gamma_{N^* \to \pi N} + \Gamma_{N^* \to \rho N}$, where $\Gamma_{N^* \to \rho N}$ is obtained from

$$\Gamma_{N^* \to \rho N}(\sqrt{s}) = \int_{2m_\pi}^{\sqrt{s}-m_N} dM \frac{d\Gamma_{N^* \to \rho N}(\sqrt{s}, M)}{dM}. \tag{8}$$

The dilepton production cross section from the direct decay of the rho meson produced from πN scattering through $N^*(1520)$ is then

$$\frac{d\sigma_{\pi N \to e^+e^- N}(s, M)}{dM} = \frac{d\sigma_{\pi N \to \rho N}(s, M)}{dM} \frac{\Gamma_{\rho \to e^+e^-}(M)}{\Gamma_{\text{tot}}^\rho(M)}. \tag{9}$$

In the above, $\Gamma_\rho^{e^+e^-}(M)$ is the dilepton decay width of a neutral rho meson of mass M. From the vector dominance model, it is given by

$$\Gamma_\rho^{e^+e^-}(M) = 8.8 \times 10^{-6} \frac{m_\rho^4}{M^3}. \tag{10}$$

For the case of free hadron masses, the dilepton invariant mass spectrum from ^{40}Ca+^{40}Ca collisions at 1 A·GeV and after correcting for the experimental acceptance filter (version 4.1) is shown in the upper part of Fig. 1. It is seen that with increasing dilepton invariant mass, the dominating contribution shifts from π^0 Dalitz decay to Δ Dalitz decay, to η Dalitz decay, and finally to direct ρ decay, as in Refs. [29,30]. In particular, the contribution from the direct decay of rho mesons produced from πN scattering through the $N^*(1520)$ (dot-dashed curve) is most important in the mass region $0.35 < M < 0.75$ GeV/c^2 and exceeds that from other ρ production channels (dashed curve) – $\pi\pi$ annihilation, pion-baryon (without $N^*(1520)$) and baryon-baryon collisions. This is different from heavy-ion collisions at CERN SPS, where dilepton production from the $\pi\pi \to \rho$ channel is more important than that from the $\pi N \to \rho N$ channel as a result of the large pion to nucleon ratio in these collisions. Compared with the experimental data the theoretical results for the total dilepton spectrum

4

are, however, about a factor of three lower in the invariant mass region $0.2 < M < 0.5$ GeV/c^2 and practically the same as in the spectral function approach of Ref. [29].

We note that contributions of other baryon resonances, e.g., the $N^*(1700)$ which also couples strongly to the rho meson [37], to low-mass dileptons are negligibly small as a result of their large masses and/or relatively weak coupling to the rho meson and nucleon.

To see how the results are modified by medium effects, we introduce the rho/omega meson in-medium masses as in Ref. [13,14] but keep the baryon masses unchanged,

$$m^*_{\rho/\omega} \sim m_{\rho/\omega}(1 - 0.18\rho_B/\rho_0). \tag{11}$$

According to Ref. [35], part of the decrease of the ρ meson mass in nuclear medium can be accounted for by the attractive interaction due to $N^*(1520)$-particle-nucleon-hole polarization. The contribution to dilepton production from πN scattering is then computed from Eqs. (1)-(10) using in-medium rho meson mass. Specifically, the rho meson mass in Eqs. (3) and (10) are replaced by the in-medium one. Also, k_ρ in Eqs. (2) and (6) are evaluated with the in-medium mass.

The reduction of omega mass enhances its production but does not significantly increase the yield of low mass dileptons due to the small partial decay width of omega meson to dileptons compared to that of rho meson. Omega mesons thus contribute to dilepton production mainly at freeze out when they have regained their free mass. Furthermore, omegas can be absorbed by nucleons. From omega photoproduction data, analyses based on the Vector-Dominance model or the additive quark model give an omega-nucleon total cross section of $25 \sim 30$ mb at omega momenta above 1 GeV/c, similar to that for the rho-nucleon total cross section obtained in the same model [38]. Also, for omega at finite momenta, its absorption cross section through the reaction $\omega N \to \pi N$ can be obtained from the inverse reaction $\pi N \to \omega N$, which has an empirical value similar to that for $\pi N \to \rho N$ (see e.g. [39]). On the other hand, for omega-nucleon scattering near threshold, Friman [40] has found from the $\pi N \to \omega N$ data that the imaginary part of the omega-nucleon scattering length is about a factor of seven smaller than that for the rho meson, giving thus a much smaller omega absorption cross section than for the rho meson. The latter result is, however, expected to change appreciably if one also takes into account final states that consists of more than one pion [41]. Since the omega contribution to low-mass dileptons is unimportant in heavy ion collisions at Bevalac energies, we have thus adopted the simple assumption that its interaction cross section with a nucleon is similar to that for a rho meson, i.e., Eq. (6). We then find that the contribution of omega mesons to dileptons are not much affected by the change of their masses and thus remains unimportant.

The dilepton invariant mass spectrum from the same reaction for the case of dropping rho meson mass is shown in the lower part of Fig. 1. We find that with dropping rho meson mass low-mass dilepton production from πN scattering through $N^*(1520)$ is substantially reduced due to a significant increase of its width. Although dileptons from other ρ production channels are enhanced, they are not sufficient to compensate for the reduction due to the broadening of N(1520). Including also the contributions from the Dalitz decays of π^0, Δ, η, and ω as well as the direct decay of ω, which are not much affected by the reduction of hadron masses, the total theoretical dilepton spectrum (solid curve) remains about a factor of three below the experimental data for $0.2 \leq M \leq 0.5$ GeV. Similar results are obtained if we also allow the nucleon and N(1520) masses to decrease according to the constituent

quark model, i.e., a factor $3/2$ reduction relative to that for the ρ meson.

In conclusion, we have shown using the HSD transport model that although dilepton production from pion-nucleon scattering through the $N^*(1520)$ is important in heavy-ion collisions at Bevalac energies, as the nucleon is the most abundant particles, including its contribution cannot explain the observed enhancement by the DLS collaboration. Allowing the reduction of rho meson mass in dense matter enhances dilepton production from other rho production channels, but it reduces significantly that from $\pi N \to N^*(1520) \to \rho N$ as a result of the broadening of $N^*(1520)$ width, leading to a total dilepton spectrum similar to that without dropping hadron masses. Thus, unlike the enhanced low mass dileptons observed in heavy ion collisions at SPS energies, which is dominated by pion-pion annihilation and can be explained by the decrease of hadron in-medium masses, the DLS result can not be explained by dropping hadron masses and remains a puzzle.

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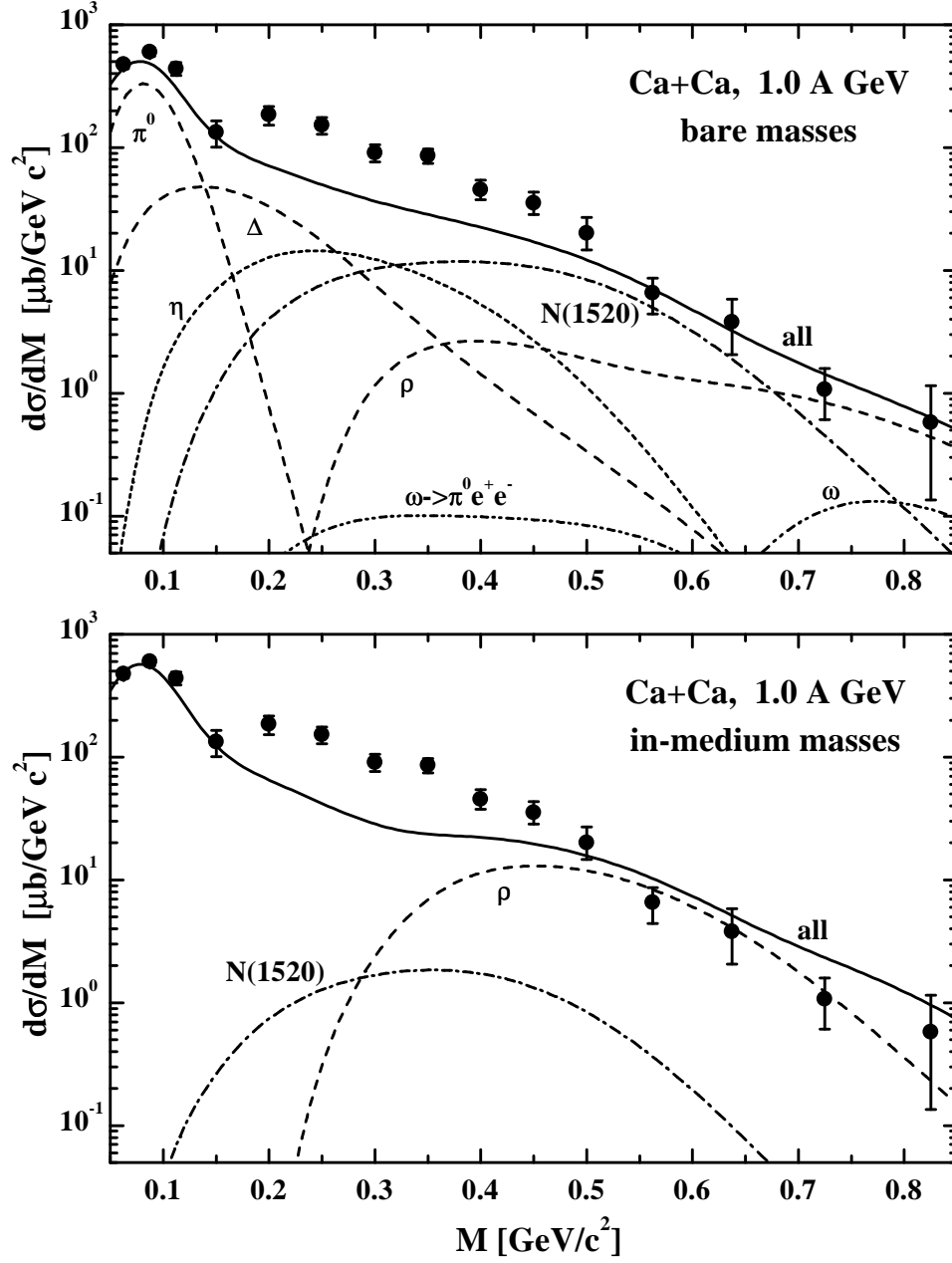FIG. 1. The dilepton invariant mass spectrum from ^{40}Ca+^{40}Ca collisions at 1 A·GeV with free (upper part) and in-medium (lower part) hadron masses in comparison to the DLS data [26].